"Variations in the Electrical Resistance of Tellurium in a Magnetic Field at Low Temperatures"

R. A. Chentsov

The results of measuring the resistance variation of tellurium in a magnetic field at liquid - helium temperatures are reported. An anomaly is found which consists of a decreasing resistance of tellurium in weak (1-2 k Oe in a transverse field) magnetic fields. This phenomenon is observed at temperatures lower than $4^{o}K$. It occurs as well in a transversal as in a longitudinal magnetic field, and is strongly dependent on the orientation of the test-sample in the magnetic field. An effect is observed in extremely pure samples. A sudden transition to saturation in longitudinal magnetic fields higher than 15 kOe is noticed. Preliminary measurements are carried out on the temperature dependency of the Hall constant and on the magnetic susceptibility of tellurium at liquid-hellium temperatures.

1. Introduction

The resistance variation of tellurium in a magnetic field[1] was the subject of research by a group of authors (Goldhammer[1], Wold[2], Beckmann[3], and others.) All of them, with the exception of Kapitza[4], worked at room temperature, and sometimes at a higher than room temperature.

Note[1]: In this work, by the "transversal effect" we mean that the magnetic field is perpendicular to the test-sample.

It was discovered that the resistance of tellurium increases in magnetic fields, according to a quadratic law, in fields of intensities, up to $H \approx 10$ k Oe:

$$\frac{\Delta r}{r} = B \cdot H^2 .$$

Characteristic is the wide discrepancies in the values of coefficient B, defined by various authors (from $1.2 \cdot 10^{-11}$ to $1.35 \cdot 10^{-10}$ CGSM). It is, therefore, necessary to stress that, in experiments by one and the same researcher, B usually increased simultaneously with increase in specific resistance (for example, in experiments of Beckmann [3] on the comparison of test-samples made of one and the same original material under different thermal conditions; and also in experiments of Wold[2] on comparing the effect of different temperatures on one and the same sample.

Kapitsa[4] examined the resistance of tellurium at temperatures ranging from room temperature to that of liquid air and in magnetic fields up to 300 kOe. It was discovered that the increasing resistance in very strong fields shows visible indications of saturation (which is not so evident for decreasing temperature.) The cooling of the sample causes a noticeable increase in the field of quadratic dependency.

Experiments on the resistance liquid of tellurium in a magnetic field at temperatures of liquid hydrogen and liquid helium have not been carried out previously. However, from the results of Kapitsa, one could expect a saturation effect in fields of an ordinary electromagnet. Former experiments in liquid helium showed, however, that saturation in fields up to 34 kOe, at temperatures up to 1.1°K are not observed. Moreover, at temperatures of liquid helium an anomaly was discovered, resulting in a decrease of the resistance of tellurium in weak magnetic fields. Inasmuch as such an occurrence was formerly known only for ferromagnetics, it seemed interesting to conduct experiments with greater care in order to prove the reality of an unusual anomaly.

2. Methods

1. Tellurium is a very peevish object for physical researches. Because of its extreme friability it is quite difficult to produce samples without cracks. The acquaintance with authors, who had the occasion to work with tellurium, convinces one that none of them was able to obtain samples without physical defects.

The imperfection of the samples was clearly revealed in the unsteadiness of their electrical resistance, for instance in the resistance's failing to return to the initial value after heating-up or cooling-off of the sample and the subsequent return to the initial temperature [5.6]. It was also shown in the unsteadiness of the specific resistance (longitudinal) of one and the same sample [7], etc. This imperfection was revealed in the contradictions in specific resistance of tellurium, as found by various authors (values vary as much as ten times). According to Wistrand [8] the magnetic susceptibility of tellurium test-samples, of which the specific electrical resistance differs three times, was the same; this shows that the examined samples differed only in extent of development of cracks.

Furthermore the physical condition of the samples is essential in studies of electrical capacities. For example one can point to Beckmann's [9] research on the influence of compression on the resistance of tellurium. The author, applying various cooling conditions, obtained a number of samples in which specific resistances differed sometimes as much as ten or more times. It appeared that the resistance of better made samples (with less cracks, i. e. with a smaller ρ) decreases with increase in the work of hydrostatic pressure,

several times lower than the resistance of samples with a large ρ. This example shows that in the study of any effect that is easily influenced by physical conditions, as the variation of resistance in a magnetic field, it is absolutely necessary to get rid of cracks in tellurium samples.

The first necessary step in this direction was to switch to monocrystals, since poly-crystal samples of tellurium, as Schmidt and Staffelbach [10] have proved, always suffer cracks, (because upon cooling, are set up in the crystalls which are due to the considerable anisotropy of the heat expansion coefficient of tellurium). However, working on growing mono-crystals of tellurium (by the methods of Obryeimov and Bridgman; i. e. by slowly cooling, starting at one end of a vertical tube, melted metal) we found that in this case also, in the process of cooling from temperature of crystallization to room temperature, tensions develop and cracks appear with all their discouraging after-effects, such as unsteadiness of resistance etc. Therefore, tests were first undertaken in growing mono-crystals of tellurium, lying loosely in a tube (a little larger in diameter than the diameter of the sample) during the crystallization process. This principle was previously adopted by Kapitza[11] during work on the growing of Vismuth mono-crystal. However, this too did not afford any substantial improvement in the samples. The cause of failure was the too strong adhesion of the glass to the melted tellurium and the sample's sticking to the lining. Substituting for the glass various other materials did not effectively change the situation at all.

A way out of the difficulty was found by employing a lining of glass powder, on which grew freely a mono-crystallic core of tellurium. In this case, although some very fine grains of glass still stick to the tellurium, the crystals are free to change position with each other,

and therefore cannot serve as a source of large tensions.

This way we were able to obtain mono-crystallic samples of tellurium quite free of cracks. Indicative of our success, for instance, was the fact that after cooling to a temperature of liquified air and consequently heating various samples, their resistance, as a rule, would repeat within limits of some tenths percent, while similar but older procedures by previous authors lead to resistance variation of some tens percent [5] and even more [6,2].

Actually, the growing of monocrystals was performed as follows: After melting and hardening tellurium metal cores 2 - 3 mm in diatmeter and 5 - 8 cm long, we placed them in a glass capillary tube. The metal was cleansed of the glass coating desolving the glass in hydrofluoric acid. The tellurium core was placed in a supported horizontal glass tube, a little larger in diameter than that of the sample; then the powder of finely pulverized glass (Pyrex) was interposed between tellurium and glass.

The tube was exhausted and then filled with hydrogen. The preheating current was switched on to heat a non-chromic coil, 1 cm long that enveloped the tube. The coil was made to move slowly (~1 mm in 1 min.) forward along the tube with the use of a special mechanism consisting of a heavy "sucker" operating on oil through a narrow opening the size of which can be changed as desired (this device was submitted to us by P. L. Kapitza).

When the coil passes over the sample the sample then melts (in the region inside of the coil) and crystallizes parallel to its length. As a result of this operation monocrystallized samples are generally produced.

In order to have the samples cylindrical and with a good elliptical profile (so that rejects may not exceed 1 - 2 percent), it is quite essential, if possible, to eliminate the friction in all moving parts (to accomplish smooth running) and to secure a uniformity of current through the coil.

The mono-crystallinity of the samples was checked by examining reflections from the facets (compare [7]), (in the case of monocrystals one can obtain because of their purity an amazingly mirror-like surface that occupies the whole profile of the sample)[2]. Also, in one case the mono-crystallinity was proved roentigenographically. A groups of samples was measured on the goniometer[3], which determines the orientations of the main (trigonal) axis of the monocrystal, relative to the axis of the sample, and other elements. The accuracy of these determinations was $\sim 2^{\circ}$. (For more detailed description of the whole method, See [12].)

2) Naturally, these mirror tests were carried out only after all testings of the sample in question were finished.

3) These testings were performed by fellow workers of the laboratory of Prof. G. B. Bokiya (IONKh,AN, USSR), to whom I express my heartiest thanks.

2. With the help of the described method a group of samples was prepared. Sample Te-1 was obtained by described method from the firm Schuchardt (Goerlitz). This sample was physically very well made relative to absence of cracks the same by having, with an accuracy xx of 0.02 percent, resistance (for $4.2^{\circ}K$) at the beginning as at the end of experiments (after pumping and other manipulations, connected with measuring); also the sample showed the same resistance function of temperature (helium) for different days of the experiment, correct to 0.03 percent and so on (samples with cracks showed variations of these

values around 1 percent and more). The good quality of this sample is assured furthermore by its small specific resistance at room temperature ($\rho = 0.020\ \Omega$-cm which is a minimum, according to cited values for pure tellurium).

Sample Te - 1 represents a mono-crystral with the main axis at an angle of 39° to the axis of the sample.

During the preparation of sample Te - 2 special attention was paid to its chemical purity. The starting material chosen was Kalbaum's tellurium, consisting mainly of 0.1 percent copper and 0.01 percent silver. This starting material was purified by means of vacuum destillation (tellurium is very volatile). From the purified material was grown a monocrystal; this time, we took as a lining a thin leaf of mica, instead of glass powder, vacuum-calcined beforehand. The monocrystal grown had its main axis almost perpendicular to the axis of the sample (at an angle of 80°); as a rule it was monocrystals just of this type that we produced in our experiments.

At the conclusion of tests the sample was exposed to a spectroscopic analysis which disclosed practically a complete absence of iron ($< 10^{-6}$) and other extremely magnetic materials (cobalt, nickel, chromium etc.). Entirely absent also was the silver which was in the starting material; the copper component was reduced to 0.002 percent. Disclosed were small traces of Sn, Si, and Mg[4]. Generally, sample Te - 2 met entirely the demands of high chemical purity. However, the sample was not entirely free of cracks (evidently in connection with the above-mentioned modification of the crystal-growing method). From a part of this sample, by means of further double recrystallization, one more sample (Te - 6) was produced. In order to have, for test purposes, Te samples containing certain metallic admixtures, samples Te - 3, Te - 4, and Te - 5 were produced. Sample Te - 3 was made to contain 0.1 percent

Fe (Te - 4 was re-crystallized three times and Te - 5 was crystallized once). Moreover, the well-known fact was confirmed that the effective purification of a crystal takes place during the growing process: thus, silver as well as iron were found extruded from the monocrystal and developed a thin pellicle or skin on the surface of the crystal. The attempt to produce samples containing iron was attended with special interest. For it is known that in the case of gold, when a decrease of resistance is observed in a magnetic field at temperatures of liquid helium, then this phenomenon is evidently related to the presence of iron in tested sample [14].

Finally, a sample was produced from alloy Te - Se (10 percent selenium). Selenium is the only element, the solubility of which in tellurium (a solid condition) is quite stable, that has been more or less investigated. [15]. Besides, selenium appears as a chemical analog, and also a crystallographic analog, of tellurium. Evidently, just because of this, it was possible to prepare a sample of Te - Se that proved to be monocrystallic. The main axis of this monocrystal almost coincided with the sample axis (the angle was only 8°) which coincidence could never be achieved by working with pure tellurium.

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4 The spectral analysis was carried out in the laboratory of spectral analysis of the Inst. Of Geological Science by Prof. S. A. Borovik, to whom I express my cordial appreciation.

Some data for samples are figured in chart 1.

Chart 1

Sample	Diameter (mm)	length (mm)	resistance (Ω · cm)	$r_{\text{liquified air}}$ / $r_{\text{room tpr.}}$	$r_{4.2^\circ K}$ / $r_{\text{room t.}}$
Te-1	3,0-2,5	65	0,020	0,341	0,496
Te-2	3,8-2,8	72	0,48	5,0	10,2
te-3	2,6	61	0,026	0,354	0,572
Te-4	2,6-2,3	24	0,11	0,385	0,605
Te-6	4,0-2,8	30	1,8	8,8	14,0
Te-Se	2,7-1,9	58	0,20	0,50	0,58

	Angle between sample axis and main axis
Te-1	39°
Te-2	80°
Te-3	--
Te-4	78°
Te-6	--
Te-Se	8°

Note To Editor
(TN: The comma is a decimal.)

3. In measuring the resistance the sample were assembled in such a way way as to avoid excessive resistances and wide variations in the coefficient of tellurium's heat expansion as the test-samples were gradually cooled to very low temperatures.

Voltage and current contacts were springs of phosphorus bronze, to a certain extent similar to those adapted by Meissner and Voigt [13]. But they were placed so as not to interfere with the free movement of the sample due to heat expansion and compression (the contacts were loosely placed on the samples which were held at one end by a spring against a cardboard holder) and gave intermittent contacts.

During resistance measurements, the voltage springs were inclined in such a way that the intermittent contacts could be, as far as

possible, on one and the same generatrix of the cylinder sample; in those cases, however, where the aim of measuring was the Hall-effect, the contact points were situated on diametrical opposite generatrices. The distance between the points of voltage contacts, lengthwise, of the sample was generally in the first case 5 - 10 mm and in the second case 3 - 5 mm.

The holder with sample was placed in the usual helium Dewar flask, in which one could obtain easily by evaporation temperatures from 4,2 to 1,8°K. The temperature was measured by the vapor pressure of the helium in the Dewar flask. The Dewarflask was located between gaps of an electromagnet which produced a magnetic field up to 7000 Oe. The magnet could rotate around the Dewar flask (having a support independent of the magnet) and the deflection angle was read off the dial, correct to 1 percent. The magnet was fed by current from an accumulator battery which maintained the necessary constancy of current.

In the system was a change-over switch that permitted, if desired, reversing the direction of the magnetic field without heeding to rotate the magnet itself. The magnetic field in the sample's zone of operation (between the voltage contacts) was homogeneous, correct to ~ 0.1 percent.

The resistance was tested by means of a potentiometer and a normal resistance. The influence of thermal e.m.f. in the galvanometer circuit was eliminated by varying the current direction. It was possible to exclude the influence of thermal e.m.f. connected with the Peltier effect at the charge and discharge of current from the tellurium, by performing testings at once, as soon as the current was passed through the sample (in determining the temperature due to the Peltier-effect, about one minute is needed.) Incidentally the last precaution

is unnecessary in helium, especially below the λ-point, where superconductivity of liquid helium secures ideal isothermal conditions for an experiment.

For metals possessing a large coefficient of the Hall effect, it is necessary to eliminate the influence of this effect during resistance measurements. The influence of the Hall effect has to do with the unavoidable arrangement of voltage contacts on one and the same generatrix of the cylindrical sample [6]. In order to eliminate the mentioned harmful influence the resistance for a given magnetic field of absolute value was measured twice for opposite field orientations, and then the arithmetical mean of the results of both measurements was taken. Furthermore, the Hall effect, linearly dependent upon, the magnetic field also discharges. On the other hand, for a varying Hall effect, characterizing an actual Hall effect, the semi-difference was taken of both of the mentioned results of measurements, since the resistance does not change during transition of the magnetic field [7]. Usually, during resistance measurements made in connection with the Hall effect, a small part resulted from the effect itself (rarely more than 10 percent). The average accuracy of resistance measurements was 0.02 percent.

3. Results

A. Variation of the Electrical Resistance of Tellurium in a Magnetic Field

1. A qualitative description of the temperature-dependency: At room temperature, and also at the temperature of liquid air, the variation of tellurium's resistance with the magnetic field[5] follows a quadratic law (BH^2) (1). (fig 1 pertains to Te - 6, but is typical for all samples). Moreover, at a low temperature the coefficient B

exceeds approximately two times the coefficient at room temperature. The magnitude for any given temperature varies noticeably from one sample to the other (at room temperature from $3 \cdot 10^{-11}$ to $2 \cdot 10^{-16}$ CGSM), which is conformed by Beckmann's observation [3].

At temperatures of liquid helium the curve of resistance verus magnetic field is maintained only in fields of 6-10 kOe, from which the coefficient B is found (in comparison with the value at the temperature of liquid air) to increase approximately twice. In more powerful fields the quadratic law gradually changes to a law, just as was discovered by Kapitza [4] for all metals in super-powerful fields at high temperatures.

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5 We are reminded that the discussion is always about a transverse effect, unless mentioned to the contrary.

Figure 1

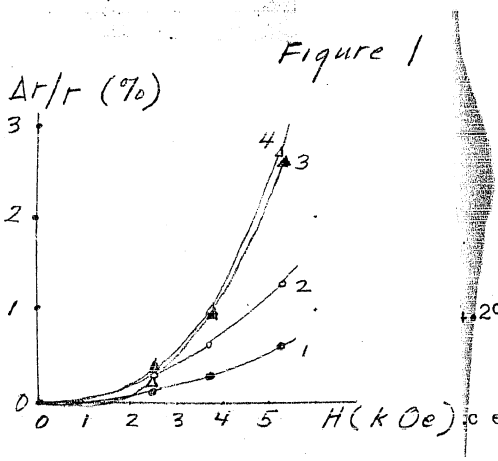

Fig. 1 ... 2° K;

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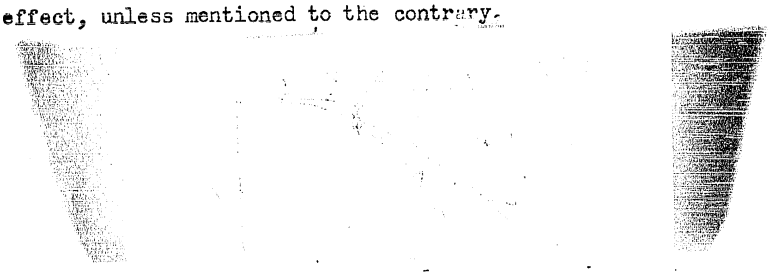


Fig. 1 1-T= 290° K; 2 - T = 83° K; 3 - T - 4.2° K; 4 - T - 213° K

In this region of the quadratic and quasi-quadratic effect ($H \geq 5$kOe) for a certain interval of low temperatures liquid helium, there is a very small temperature-dependency; that is, resistance increases for a decrease of temperature from T=4° to T=2° K only 5-10 percent.

On the other hand, in a region of weak magnetic fields this amount of temperature variation (that is, 4° to 2° K) causes a considerable

variation in the curve of resistance versus the magnetic field. Even at 4.2°K the curve is of an entirely different character; that is, the increase of resistance develops considerably more slowly than it is supposed to be according to the quadratic law. With decrease in temperature the curve approaches more and more the H axis and intercepts it at a certain temperature (around 4°K), thus entering the region of negative effect increases; and at T 2°K it covers the range of magnetic field values until H≈2kOe and also the variation resistance range until $(-\Delta r/r)\approx 1\cdot 10^{-3}$.)

2. The effect of decreasing resistance in tellurium in a magnetic field and at low temperatures: The described abnormal occurrence of decreasing resistance in tellurium in a magnetic field was invariably observed in all pure samples at liquid-helium temperatures. Moreover, the effect was accurately reproduced upon repetition of tests, as seen in fig. 2 which shows the resistance variation of sample Te-1 in a magnetic field and at a temperature of 2.13°K.

The general nature of the temperature dependency (for constant orientation of magnetic field and sample) is illustrated in fig. 3. The abnormal negative effect appears at Temperature T≈4°K (sometimes, as in the quoted incident of sample Te-1, even at 4.2°K). The effect increases steadily for further temperature decrease. In addition, the magnetic field intensity, according to the resistance minimum, depends very little on the temperature.

The abnormal effect depends very strongly on the orientation of the sample in the magnetic field. As seen in fig. 4 (referring to sample Te-2 at T = 2.15°K) one can obtain, by revolving the field around the sample at constant temperature, a variation of $(-\Delta r/r)_{max}$ twice.

We found quite accurately the values of the maximum resistance decrements ($-\Delta r/r)_{MAX}$ at T 2°K for various samples of pure tellurium (chart 2), especially for samples with close orientations (Te-2 and Te-4).

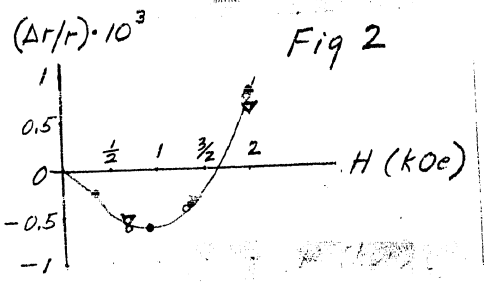


Fig 2

Chart 2

Decrease in resistance of Tellurium in a Magnetic Field

Sample	Temperature (K)	Maximal decrease in resistance
Te-1	2.13	$0.7 \cdot 10^{-3}$
Te-2	2.15	$1.0 \cdot 10^{-2}$ (sic)
Te-4	1.96	$1.1 \cdot 10^{-3}$
Te-5	1.96	$0.5 \cdot 10^{-3}$

Considering the fact that a decrease in resistance of tellurium in a magnetic field was observed in all samples and remembering the peculiarities in the methods of producing each every sample, we have to acknowledge the reality of the established abnormal effect.

Since the abnormal effect was observed even in sample Te-1, which possessed good physical qualities (absence of cracks), then the effect must not be connected with the physical imperfection of the samples (for instance with cracks). Since the anomaly was also observed in sample Te-2, which consisted of chemically very pure material, the abnormal effect must undoubtedly not be brought about

through soiling in the sample-material and, especially, must not be connected with ferro-magnetic admixtures. The last conclusion confirms, thus, that the abnormal effect in sample Te-4 is twice as large as that in the prepared analoguous method, but is somewhat smaller than that in the pure sample Te-5 (see division 2,2). Finally, one has to explain in this sense the absence of abnormal effect in Te-Se (see further div. 3, A, 4).

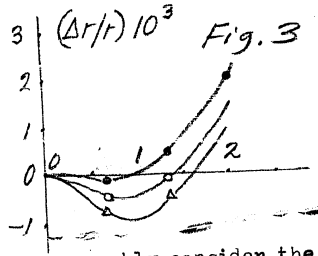
In this connection it is worth-while to mention two experiments on the influence of the sample's orientation in the magnetic field on the effect under consideration, performed with sample Te-1. Both experiments differed only in that the potential points of the second experiment were turned 90° relative to the first experiment. Inspite of this modification the minima and maxima of the abnormal effect in the orientation diagram preserved their original value regardless of when the tests were made. This, once more, verified that the considered anomaly is not connected with any methodological or experimental error. Just this is also shown from the adequate quantitative correspondence of the effect for samples Te-3 and Te-4, both samples possessing identical orientation, but very great difference in the degree of perfection (see chart 1) and in the magnitude of the Hall-effect (see further on chart 3). This circumstance shows that the Hall effect in the described experiments on the resistance of samples in a magnetic field was eliminated and that the Hall effect did not affect the examined electromagnetic anomaly. Moreover this comparison of Te-2 and Te-4 shows that the described anomaly of tellurium is not a structure-sensitive effect (that is, an effect that is easily influenced by physical conditions such as presence of cracks, impuritites, etc.).

The abnormal decrease of tellurium resistance at temperatures of

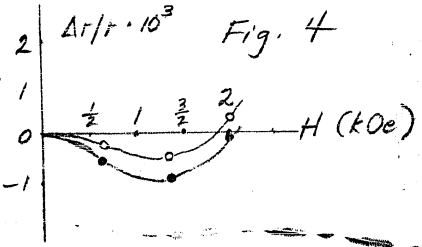
liquid helium occurs also in a longitudinal magnetic field. As seen in fig. 5, pertaining to sample Te-1 and to temperatures 4,2 and 2,06°K, the anomaly in the longitudinal field is similar to the somewhat higher temperature (it is already quite noticeable at 4.2°K), which gives big values of $(-\Delta r/r)_{max}$; the range of the anomaly covers stronger magnetic fields (up to 6-7 kOe). The fact that resistance descreases in tellurium occurs in longitudinal as well as in transverse magnetic fields definitely helps substantiate the existence of this electromagnetic anomaly.

3. Research on saturation in strong magnetic fields:

As indicated in the Introduction, the first attempts fail to disclose any saturation in the temperature-versus-resistance variation of tellurium in ordinary magnetic fields (temperatures of liquid helium). This question was re-examined on sample Te-1. It was again confirmed that there are no signs of saturation whatsoever for H up to 22 kOe and for T= 1.43°K (fig. 6) in the case of the transverse effect. A study of the curve describing the approximate formula $\Delta r/r =$ const H^n where n is a function of H reveals that n monotonically decreases with increase in H. In a range of magnetic field strengths from 6 to 11 kOe



$(\Delta r/r)\,10^3$ Fig. 3



$\Delta r/r \cdot 10^3$ Fig. 4

one can roughly consider the dependency as quadratic (that is, H^2) and between 13 and 22 kOe the curve tends to follow the sesqui-square ($H^{1.5}$) law (that is, the curve is semi-cubic).

As already indicated before, the curve describing the transverse effect (for powerful fields) depends very little on temperature in the range of very low temperatures of liquid helium.

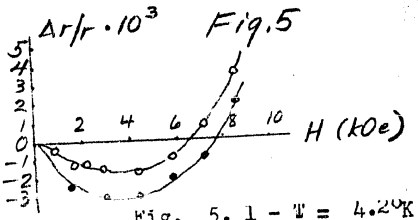


Fig. 5. 1 - T = 4.20°K;
2 - T = 2.06°K

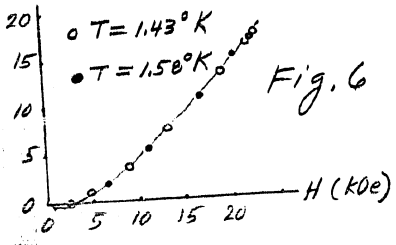


Fig. 6

The longitudinal effect in powerful magnetic fields where r 0) were also investigated. In contrast to the transverse effect, at 4.20 and 2.02°K there is observed an obvious transition to saturation in magnetic fields of 15kOe (fig 7). The resistance increment in the longitudinal effect in powerful magnetic fields is 1/5 to 1/6 of the intersectional effect. This coincides qualitatively with Heaps' [18] observation - the only author investigating previously (and even then only at room temperature) the longitudinal effect in tellurium.

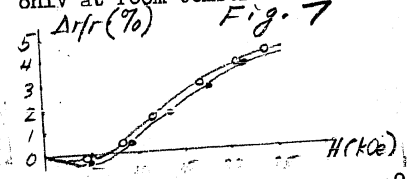


Fig. 7. 1 - T = 4,2°K;
2 - T = 2,02° K

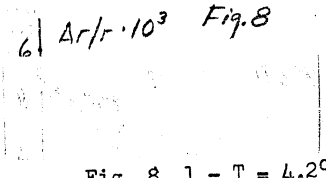


Fig. 8 1 - T = 4,2°K; 2-T =2,05°K; 3-T = 1,5°K; 4-T= 1,2°K

NOTE:

4. Fusion of tellurium with selenium: The resistance variation of sample Te-Se in a transverse magnetic field (fig. 8) was entirely different from that in samples of pure tellurium. In the first place, the abnormal negative effect was entirely absent. In the second place, the resistance-increase with magnetic field strength was approximately linear for all temperatures of liquid helium. Third, the intensity of the effect increased quickly with temperature decrease (somewhat more rapidly than 1/T).

As already indicated before, the curve describing the transverse effect (for powerful fields) depends very little on temperature in the range of very low temperatures of liquid helium.

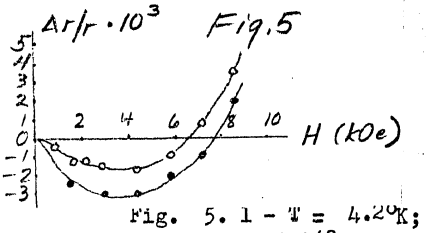


Fig. 5. 1 - T = 4.20°K;
2 - T = 2.06°K

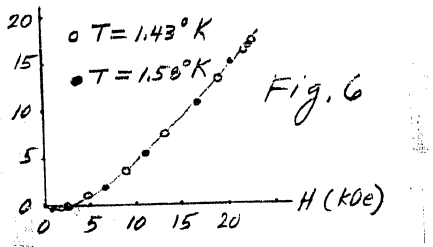


Fig. 6

The longitudinal effect in powerful magnetic fields where r 0) were also investigated. In contrast to the transverse effect, at 4.20 and 2.02°K there is observed an obvious transition to saturation in magnetic fields of 15kOe (fig 7). The resistance increment in the longitudinal effect in powerful magnetic fields is 1/5 to 1/6 of the intersectional effect. This coincides qualitatively with Heaps' [18] observation - the only author investigating previously (and even then only at room temperature) the longitudinal effect in tellurium.

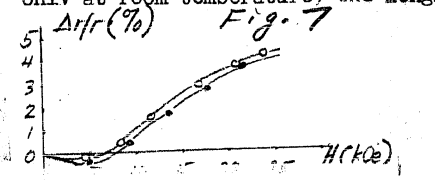
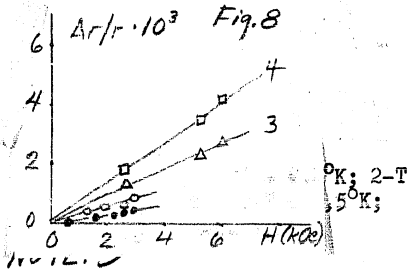


Fig. 7. 1 - T = 4,2°K;
2 - T = 2,02° K



°K; 2-T
5°K;

4. Fusion of tellurium with selenium: The resistance variation of sample Te-Se in a transverse magnetic field (fig. 8) was entirely different from that in samples of pure tellurium. In the first place, the abnormal negative effect was entirely absent. In the second place, the resistance-increase with magnetic field strength was approximately linear for all temperatures of liquid helium. Third, the intensity of the effect increased quickly with temperature decrease (somewhat more rapidly than 1/T).

B Other Results

1. Specific resistance of tellurium and the temperature-dependence of resistance: Chart 1 shows how greatly the values of specific resistance in various samples of tellurium can fluctuate. Whereas in Te-1 ρ was 0.020 Ω · cm. at room temperature, ρ_{room} in sample Te-6 was 1.8 Ω cm at room temperature. This divergence between the samples increased even more for temperatures of liquified air and still more for liquified helium. It was easy to show that samples differing especially in large specific resistance also differed at the same time in large resistance instability, which fact indicates the presence of cracks in them. On the contrary sample Te-1 possessed a smaller value of specific resistance than any cited in literature.

The temperature dependence of resistance of various samples, as seen from the same chart 1, also varied very much. The temperature coefficient at room temperature varied for different samples in magnitude, and even in sign. The majority of samples had a normal metallic (positive) coefficient; however, this was not the case for samples with cracks (Te-6 and Te-2). The most natural explanation of this relation to resistance-temperature coefficient, from the point of development of cracks in the sample, is the assumption that temperature decrease somehow helps to reveal these cracks, which gives a negative temperature coefficient. Upon subsequent warming to original temperature these cracks must remain somewhat more exposed than the original cracks, which fact is revealed in the increase of resistance over initial resistance.

For sample Te-1 free of cracks the temperature coefficient of resistance at room temperature was 0.0032, which co-incides with the

value obtained by Lange and Heller [19], who work with tellurium under strong pressure to prevent crack-development.

A positive temperature coefficient for samples observed at room temperature was also maintained during temperatures liquid air. However at temperatures of liquid helium all samples without exception had a negative coefficient (similar to results of Meissner and Voigt [13]). From this it follows that somewhere between the temperature of liquid air and that of liquified helium (approx. at 40 - 60°K) one should find m i n i m u m resistance. This value was determined previously by Kammerlingh - Onnes and Backmann [5] and by Meissner and Voigt [13]. The fact that the minimum occurs in sample Te-1, which is free of cracks and sufficiently pure chemically and also the fact that its conditions apparently differs little for samples of the mentioned authors and ours make one think that this minimum really exists.

Sample Te-1 has at 4.2°K a temperature coefficient of resistance equal to 0.0047. With decrease of temperature this coefficient decreases noticeably (in absolute magnitude) and at 1.5°K it was only 0.0013 (fig. 9). An impression was created that it converges to zero at 0°K. On the other hand, the resistance of sample Te-2 for decreasing temperature (in the temperature range of liquid helium) increased rapidly and progressively.

2. The H a l l E f f e c t. The Hall electromotive force was measured by the same potentiometrical method as the resistance variation in a magnetic field, but differing in layout of the potential contacts and in the processing of the results of measurements (div. 2 at 3). The current through the sample was measured by milliammeter. The Hall effect constant was estimated by means of formula

$$R = (\pi/4)\,(V_H \delta/IH)$$

(V_H - Hall electromotive force, δ - diameter of sample in direction of potential contacts, i. e. perpendicular to the magnetic field H, I - measured current; multiplier $\pi/4$, in connection with electric currents, results from the circular, not the usual rectangular, section of the sample. This is a roughly estimated formula, since it does not take into consideration, that the Hall electric field perpendicular to the current is not in the case of anisotropic media strictly perpendicular to the magnetic field. Nevertheless it gives an entirely correct idea of the order of magnitude of the Hall-effect and of its temporary dependency (at constant orientation).

Results for certain samples are indicated in chart 3, giving R in CGSM units. The sign of the Hall effect is in all cases positive.

Chart 3

Temperature (°K	R (in CGSM units) Te-1	Te-4	Te-2
Room	300	850	$8.5 \cdot 10^2$
of liquid air	450	1100	$1.5 \cdot 10^1$
of liquid helium	(500)	1200	$1 \cdot 10^5$

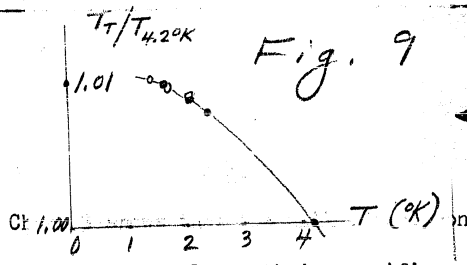


Fig. 9

← Fig. 9

Ch nstants for various samples differ just as sharply as their specific resistances, and also the divergence with decrease in temperature. The Hall effect constant in sample Te-2 at a temperature of liquid helium reaches an immense value - 100 000 CGSM; as far as we know, all values of the Hall effect constant

increase at such temperatures for various metallic and non-metallic conductors.

We could confirm for temperatures of liquid helium the observation made previously for temperatures of liquid hydrogen by Kamerlingh-Onnes and Beckmann [5] that revealed a saturation of the Hall effect; i. e., the decrease of the Hall effect constant in powerful magnetic field, equaled, in tests of the mentioned authors, 3 percent in magnetic field of strength H = 10 kOe. This phenomenon appears in all samples investigated by me in liquid helium. For a magnetic field of strength In H = 5 kOe the Hall constant was 5 - 7 percent smaller than the constant for a weak field. It is only natural to correlate this phenomenon of saturation in the Hall effect in tellurium with the phenomenon of saturation in the resistance variation of tellurium in a longitudinal magnetic field, as it was observed by us (see div. 3, A, 3) at temperatures of liquid helium; also it must be correlated with the saturation of the transverse effect in super powerful fields at higher temperatures, as discovered by Kapitza [4] (compare div. 1).

It was disclosed that the constant of the Hall effect in tellurium, within the limits of precision of these measurements ($\approx$3 percent) is independent of temperature around the temperatures of liquid helium (between 4.2° and 2°K). The last observation seems to be of special interest, if we remember that the resistance of tellurium in this interval of temperatures varies quite noticeably (for example, in sample Te-2, almost twice).

3. M a g n e t i c s u s c e p t i b i l i t y of t e l l u r i u m. The Magnetic susceptibility of tellurium (sample Te-1) was measured at temperatures 4.2 and 2.10°K (Tr. Note: ? Hui ?) The measurements were performed by the Gue method, utilizing a great l[illegible] length of the sample (of which one end is in an approximately homogenous field and the other end is in a field approximately equal to zero). The force was measured with the help of special sensitive weights

with an optical scale, placed at our disposal through the courtesy of P. L. Kapitza.

It was determined: 1) For both temperatures and for all utilized magnetic fields (from 200 Oe to 5 kOe) the susceptibility of tellurium is negative (causes an extrusion of the sample from the magnetic field).

2) The diamagnetic susceptibility in the indicated range of magnetic field strengths is independent of temperature (points corresponding with both above-indicated temperatures cover one and the same constant).

3) The diamagnetic susceptibility in the indicated range of magnetic field strength (the force varies with the square of intensity (strength) of the magnetic field). This result is reliably established for fields of 200-1200 Oe; large fields strenths give small variations (not more than 25 percent), seemingly due to the smallness of the interval of linear proportionality between force and variation in these exceedingly sensitive scales.

4. Conclusion

1. A new method is being worked out to grow monocrystals, which should introduce the development of the Kapitza system. The new method enabled us to obtain samples of tellurium better made than samples of former authors (a smaller specific electrical resistance at room temperature, a less residual resistance at 4,2°K, resistance stability etc.).

2. The performed measurements of resistance variations with temperature for various tellurium samples, also for a sample of tellurium and selenium alloy, revealed in magnetic fields at temperatures of liquid helium an electromagnetic anomaly of tellurium: that is, a resistance decrease in weak magnetic fields ($H \approx 1 - 2$kOe for a transverse

magnetic field). This phenomenon is not observed at high temperatures, but appears at T ≈4°K and becomes more evident with further cooling down to T≈2°K. This phenomenon is observed as well in transverse as in longitudinal magnetic fields and is strongly dependent on the sample's orientation in the magnetic field. It is observed in samples chemically and physically pure. One may apparently consider its reality as established.

The normal (positive) resistance variation occurring in stronger magnetic fields (transverse effect) at temperatures of liquid helium is approximately two times greater than the resistance variation at temperatures of liquid air. It is very slightly dependent on temperature in the range of liquid-helium temperatures. The saturation of the effect is not observed until H = 22 kOe and T = 1.43° K. The longitudinal effect in fields H 15 kOe shows a definite transition to saturation.

The resistance dependency of the tellurium-selenium alloy on the transversal magnetic field at temperatures of liquid helium is identified. The effect starting with very small fields is linearly proportional to field intensity and is strongly dependent on the temperature in the range 4.2 - 1.2°K.

3. Rough calculations are worked out for the dependence of temperature resistance on the Hall effect and magnetic susceptibility of tellurium at temperatures of liquid helium.

It is shown that: a) The temperature coefficient of tellurium is positive at room temperature and negative at liquid helium temperatures. b) The resistance of Te is a minimum in the range 40 - 60° K.

It is determined that the constant of the Hall effect in tellurium is independent of the temperature between 4° and 2° K. The saturation

of the Hall effect in strong fields, which was observed before at temperatures of liquid hydrogen, becomes even more evident at liquid helium temperatures.

The diamagnetic susceptibility of tellurium proved to be independent of temperature, between 4° and 2°K.

Quite interesting is the known resemblance between electromagnetic and magnetic anomalies (the so called effect of de Haas and van Alphen, [20-22], observed in bismuth in connection with the electromagnetic anomaly in tellurium. Thus: 1) Both anomalies are observed only at sufficiently low temperatures and they disappear gradually slightly at higher temperatures. 2) The condition of irregularities (in a magnetic field) is roughly independent of the temperature. 3) The effect in weak fields is more sensitive to temperature than the effect in powerful fields. The abnormal effect is observed in both cases only in sufficiently pure samples and at the same time the effect is not too sensitive to the physcial condition of the crystal. 5) Finally, both of the abnormal effects are strongly dependent on the sample's orientation in the magnetic field.

Based on this analogy, which hardly can be accidental, one can regard as most desirable three directions of future experimental researches on the anomaly of tellurium. First it is advisable to continue the study of the anomaly at even lower temperatures, where an appearance of new peculiarities can be expected. Secondly, one has to study elaborately the influence of the current orientation and of the magnetic field relative to the crystallographic axes on the anomaly in question, which is absolutely necessary for forming a theory of this phenomenon. In the third place, one has to investigate carefully the magnetic characteristics of tellurium at liquid-helium temperatures. If the nature of electromagnetic anomalies of tellurium and bismuth is identical, one can hope for a discovery of anomalies

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in the magnetic susceptibility of tellurium.

In conclusion I regard it as my pleasant duty to express thanks to the academician P. L. Kapitza for his guidance and constant interest in the work and also to Prof. A. I. Shal'nikov and S. I. Filimonov for their valuable practical advices.

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